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Attenuation of Traffic Induced Ground Borne Vibrations due to Heavy Vehicles

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Fifth International Conference on
Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics
and Symposium in Honor of Professor I.M. Idriss
May 24-29, 2010 • San Diego, California

ATTENUATION OF TRAFFIC INDUCED GROUND BORNE VIBRATIONS DUE TO HEAVY VEHICLES

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ABSTRACT

Traffic induced vibrations, which are transmitted through the ground, may interfere with the proper operation of vibration sensitive equipments and cause nuisance on local population. Influence of these vibrations on surrounding buildings and sensitive devices play an important role on acceptance of the projects. In this study, main objective is the estimation of ground-borne vibration levels due to operation of heavy vehicles at two different sites where soil type and stratification significantly differs. For this purpose, site specific vibration surveys are conducted. A series of dynamic finite element modeling analyses are performed to predict actual vibration records at measurement points. Parameters used in finite element modeling are obtained through geotechnical and geophysical surveys conducted at the site. Modeling results are in good agreement with the actual vibration levels in the considered frequency range. Frequency range of dominant structural responses due to ground borne vibrations induced by heavy vehicles is found to be between 10 Hz to 50 Hz for a single degree of freedom system with 3% damping. Calibrated finite element models are further used to predict the attenuation of vibrations with distance from the source. Slightly better wave attenuation is observed in soil site compared to the rock site.

INTRODUCTION

According to Bungum et al. (1985) vibrations from external sources can be classified in general three groups according to their frequency content. Low frequency vibrations in the ground are considered to have frequency content smaller than 2 Hz. These may be background vibrations or tidal waves due to ocean waves. Second category vibrations are cultural background vibrations induced from traffic and industrial activities with frequencies greater than 2 Hz. Most extreme category involves earthquakes, blasts, thunder bolts and soon.

Ground-borne vibrations are considered to be a serious problem for vibration sensitive devices such as coordinate measurement devices, optical laboratory equipments and industrial precision laser cutting machines. Some common sources of ground-borne vibrations are trains, heavy vehicles such as trucks, earth-moving equipments moving on palettes on rough or paved roads.

The amount of energy that is transmitted from operating vehicles to the ground is dependent on the smoothness of the surface, the type of the movement system (tires or palettes) and resonant frequencies of the vehicle suspension system. Soil properties strongly affect the transmission of vibration due to vehicle activities. Operation of these vehicles creates vibrations that propagate through the various rock and soil strata to the foundations of the nearby buildings. Vibration amplitudes of floors and walls of the building structures often will coincide with the resonant frequencies of the various components of the buildings and this will cause detrimental effects on vibration sensitive devices, human and even structural components of the buildings (Transit Noise and Vibration Impact Assesment , 2006). There is an increasing demand on reducing effects of vibrations imposed by traffic. Active and passive vibration isolation techniques are utilized to minimize the detrimental effects of traffic induced vibrations on civil engineering structures.

AIM OF THE STUDY

Seismic wave amplitudes are reduced as waves propagate through soil medium. The reduction in wave amplitudes is a consequence of energy losses in soil and named as attenuation. Attenuation of waves in geotechnical materials is a complex phenomenon resulting from interaction of several mechanisms that influence energy dissipation of soils. In this study, main objective is the estimation of ground-borne vibration levels due to operation of heavy vehicles at two different sites. For this purpose, site specific vibration surveys are conducted at selected locations in the site. A series of dynamic finite element modeling analyses are performed for predicting actual vibration recordings at different measurement points on the ground. Parameters used in finite element modeling are obtained through geotechnical and geophysical surveys conducted at the site. Calibrated finite element models are further used for predicting the attenuation of vibrations with distance from the source.

PREVIOUS STUDIES ON TRAFFIC INDUCED VIBRATIONS

Heavy vehicle induced vibrations were measured experimentally by Whiffin and Leonard (1971) on a trunk road in England. On flexible and rigid pavements, artificial ramps are located and the peak particle velocities are measured in close to the road side. It was observed that the height of surface irregularities and the velocity of the vehicle are more dominant than the roughness of the pavement for increasing peak particle velocities observed in proximity of the road. Watts (1987) observed that in daily traffic, heavy vehicles produce most of the perceptible vibrations. As a result of his experiments, it was noticed that the surface irregularities with a depth/height of 20 mm which are within 5 m distance to a building, perceptible vibrations were measured. In another study, Watts (1992) proposed simple prediction models which take into account the maximum height/depth of the irregularities on the road over which the heavy vehicle passes the speed of the vehicle and the distance between the surface irregularity and the measurement point. Crispino and D'apuzzo (2001) obtained vibration velocities by the transit of heavy vehicles (mainly buses and tracks) and extended the prediction models of Watts.

Hunt (1991) and Hao (1998) have proposed numerical models for the prediction of free field traffic induced vibrations. In these studies, road unevenness was described in a stochastic method by utilizing power spectral density function.

Watts and Krylov (2000) have studied the effects of road humps and speed control cushions and compared the responses with numerical findings. In their study, an empirical relation was derived for predicting the effects of sites with different soil conditions for determining the determination of minimum distances of speed control cushions and road humps from building foundations.

Lombaert and Degrande (2003) developed an advanced numerical model accounting the dynamic road-soil interaction and validated for the layered structure of soil. Importance is given to various parameters related to the vehicles, road and the soil. An experimental program was also followed to check the predictive quality of their model and it is found that the prediction model describes the physical phenomena with very reasonable accuracy

VIBRATION MEASUREMENTS

In this study, an extensive measurement program was carried out for estimating and predicting the vibration levels at probable locations for the foundation of a vibration sensitive device. The objective of the measurements was to map the ground-borne vibrations due to external vibration sources at selected points. Vibration measurements are performed in two different sites where soil type and stratification significantly differs. At the beginning of the measurements, geotechnical and geophysical surveys are conducted in the sites. Summary of the surveys are given in the following parts.

Summary of Geotechnical and Geophysical Surveys

SPT tests are performed at the sites and lab tests are conducted on samples at different depths to obtain unit weight, soil classification and undrained shear strength of soils. SPT logs are obtained up to 20 meters in each site.

Geophysical measurements are performed at three sites which are different in soil and rock stratification. Firstly, seismic refraction tests conducted to obtain shear wave profile of the sites. S-wave refraction test simply evaluates the shear wave generated by the seismic source located at a known distance from the array. The wave is generated by striking a hammer horizontally on the ground surface to induce the shear wave. Shear wave profiles at these sites obtained from seismic refraction tests at these sites are shown In Fig.1. Secondly, micro tremor tests were conducted to obtain dynamic properties of the site such as predominant period and amplitude. Micro tremors are low amplitude (in the order of microns) ambient vibrations of the ground caused by man-made or atmospheric disturbances. In each site micro tremor measurements are performed at three points. Natural dominant periods of the sites are shown in Table 1.

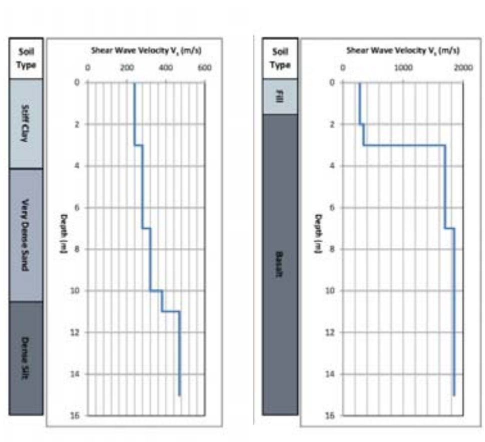

Figure 1 Shear Wave Profile of Sites (A) and (B)

Table 1 Natural Dominant Frequency for sites A and B

Site	Natural Period (s)
A	0.71
B	0.29

Table 2 Geotechnical Attributes of site A

Depth(m)	Soil Type	Unit weight (kPa)	Groundwater condition	Shear wave velocity Vs (m/s)	Compressional (P-wave) Wave Velocity (m/s)	SPT N60	Bearing Capacity (kPa)
0-4	Medium Clay	17.5	No groundwater	240-280	420-500	21-50	200 kPa
4-10	Dense Sand	18	No groundwater	280-320	440-520	>50	-
10-20	Very Dense Silt	18	No groundwater	380-470	800-910	>50	-

Table 3 Geotechnical Attributes of site B

Depth(m)	Soil Type	Unit weight (kPa)	Groundwater condition	Shear wave velocity Vs (m/s)	Compressional (P-wave) Wave Velocity (m/s)	SPT N60	Bearing Capacity (kPa)
0-2	Gravelly sand	18.1	No groundwater	280-340	440-610	45-50	1000 kPa
2-15	Basalt	17.5	No groundwater	1700-2000	3600-3900	>50	-

Vibration Measurements at the Site

Bruel and Kjaer 8340 Seismic Accelerometers which can record accelerations up to 0.5 g in a frequency interval between 0.1 Hz to 1500 Hz are used for vibration monitoring. The sensors were located on orthogonal axes in North-South, East-West and in the vertical direction. Measurements are performed in three axes simultaneously. In recordings, north is labeled as X-Axis, east is labeled as Y-Axis, and the vertical axis is labeled as Z-Axis. Sensors are positioned on an aluminum cube of 98 mm dimension and this assembly is mounted on a concrete block which is buried 50 cm into the ground. In each site, three locations are selected for vibration monitoring. Positions of the accelerometers at site A and B are shown in Fig.2 and Fig.3. Vibration measurement setup is depicted in Fig.4. In each site, first measurement points are located very close to the moving vibration source for determining the peak acceleration amplitude levels caused by the heavy vehicle. Second and third measurement points are located at various distances from the source and vibrations measurements are conducted simultaneously at all of the points for duration of five minutes. Moving source is cycled during the measurement period.

In Fig. 5 and Fig. 6, sample vibration measurement records are depicted as frequency-acceleration amplitude plots. Vibration amplitudes are in micro g levels and may be considered small compared to earthquake records, however proper operation of many vibration sensitive devices require base vibration levels in micro g levels.

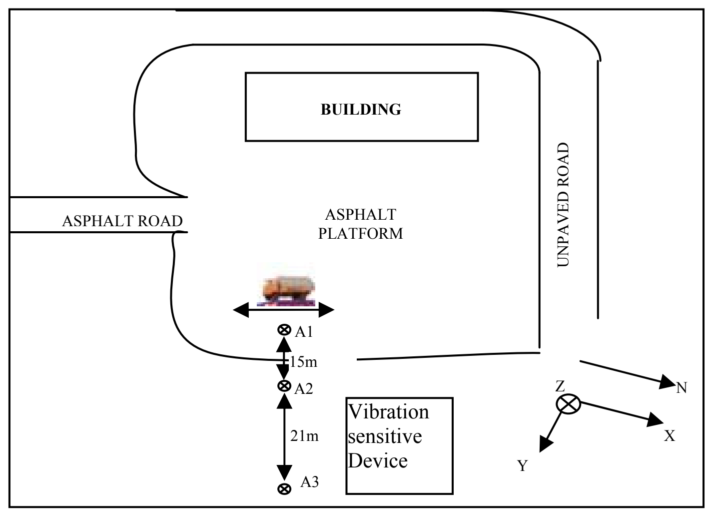

Fig. 2 Vibration monitoring locations at site A

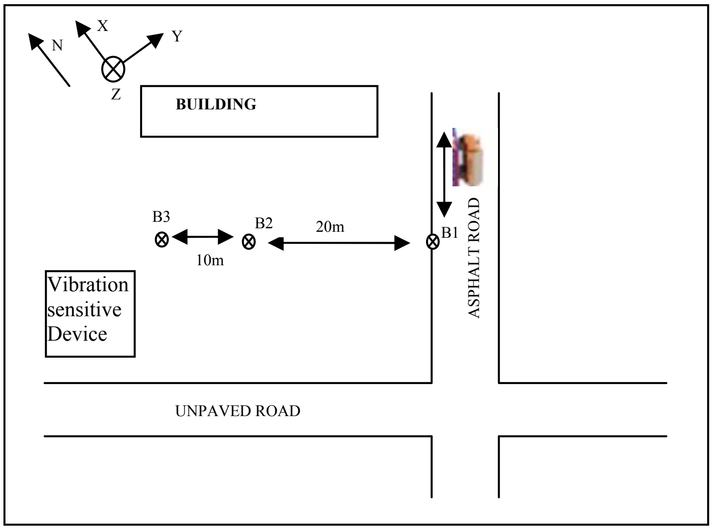

Fig. 3 Vibration monitoring locations at site B

Fig. 4 Vibration measurement setup

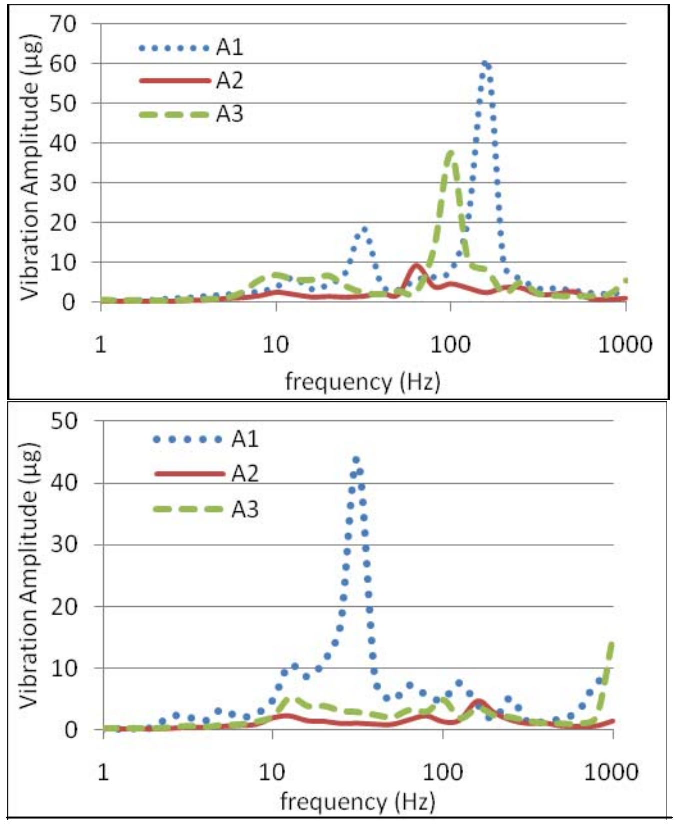

Fig. 5 Site A vibration levels recorded in horizontal and vertical axes (respectively) while truck moves on asphalt road

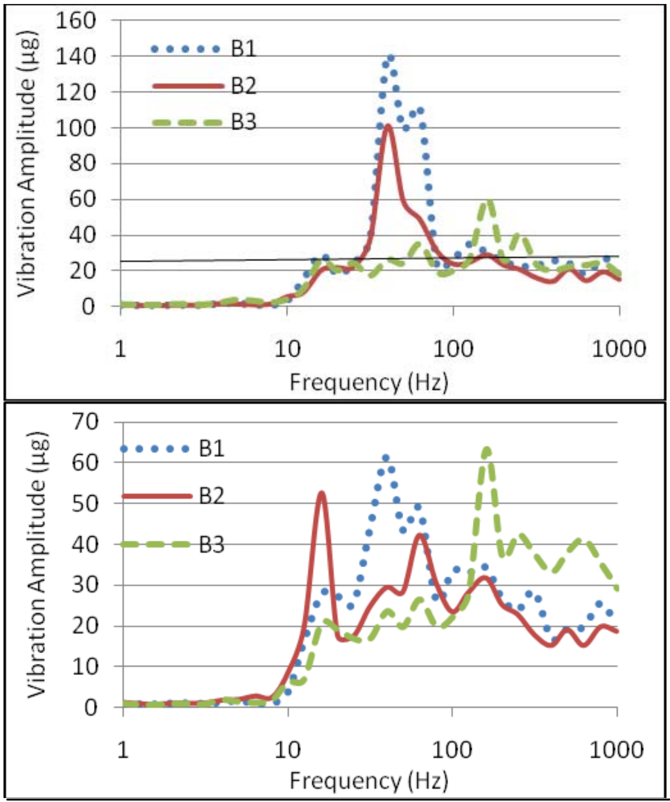

Fig. 6 Site B vibration levels recorded in horizontal and vertical axes (respectively) while truck moves on asphalt road

NUMERICAL MODELING STUDY OF GROUND-BORNE VIBRATIONS

In this part of the study, wave propagation at sites A and B are modeled by PLAXIS Dynamic Finite Element Code. Soil stratification and shear wave velocity values of the considered soil layers are included in the model. Horizontal length of the modeled geometry is 130 m and total depth is 20 m. Absorbent boundary conditions are defined in the models for taking into account the wave radiations.

In Plaxis software, soil damping is modeled via use of Rayleigh damping coefficients. In the analyses, α and β parameters are selected for accounting 4% to 5 % overall damping in the considered frequency range. Parameters used in the analyses are shown in Table 5.

Acceleration time history recorded at the C1 measurement point is used as input motion in the model at selected node. For a comparison of analyses results with the measurements at C2 and C3 points, corresponding nodes are selected in the finite element model and acceleration time history at these nodes were obtained. A simple sketch of the finite element model is shown in Fig. 7.

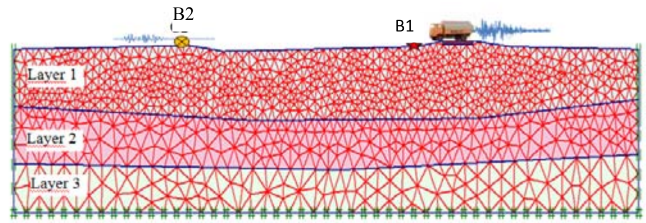

Fig. 7 An illustration of a scenario on the finite element model

Table 5 Finite element modeling parameters for site A

Layer #	γ (kN/m^3)	V_s (m/s)	ν
1	17	250	0.33
2	18	320	0.33
3	18.5	480	0.33

Table 6 Finite element modeling parameters for site B

Layer #	γ (kN/m^3)	V_s (m/s)	ν
1	18,1	310	0.33
2	17.5	1900	0.30

In Fig. 8 and Fig. 9, frequency-amplitude plots for actual measurement record and finite element analysis are depicted. Finite element modeling results are in good agreement with the actual acceleration measurements in the frequency range considered.

Response spectra of the measured and computed motions for 3% damping are obtained for comparison, as shown in Figures 11 and 12. An investigation of the response spectra reveals that dominant responses due to ground borne vibrations induced by these vehicles are in a frequency range of 10 Hz to 50 Hz.

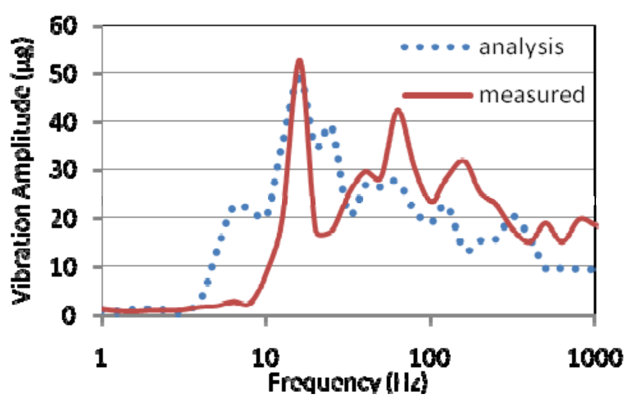

Fig. 8 Frequency-amplitude plots (Z-Axis) at B2

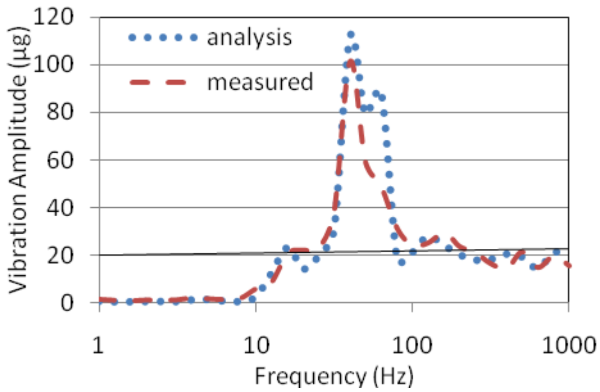

Fig. 9 Frequency-amplitude plots (X-Axis) at B2

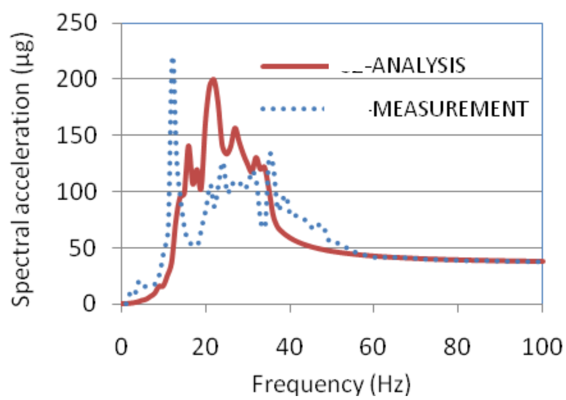

Figure 10 Comparison of response Spectra for B2 (Z-Axis)

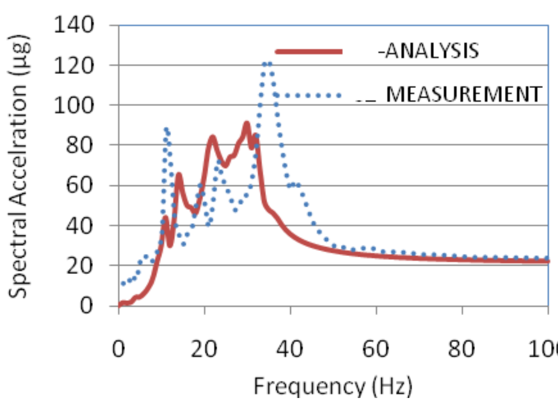

Figure 11 Comparison of response Spectra for B2 (X-Axis)

MODELING ATTENUATION OF GROUND BORNE VIBRATIONS VIA DYNAMIC FINITE ELEMENT ANALYSES

Based on the comparisons of the frequency-amplitude plots for the actual measurements at the sites and the dynamic finite element analysis results, further analyses are conducted by using the calibrated finite element models for site A and site B. Acceleration amplitudes at points on various distances to the vibration source were obtained through finite element modeling. In Figures 12 to 15, rms acceleration levels at different distances to vibration source are depicted together with a functional fit and 95% confidence intervals.

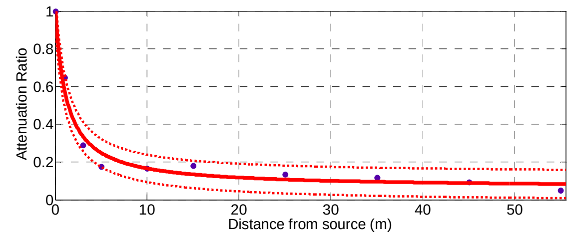

Fig. 12 Attenuation of vibrations for Site A (Vertical axis)

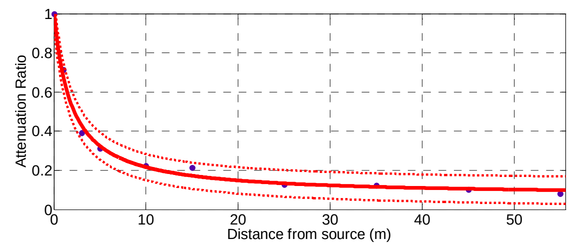

Fig. 13 Attenuation of vibrations for Site A (Horizontal axis)

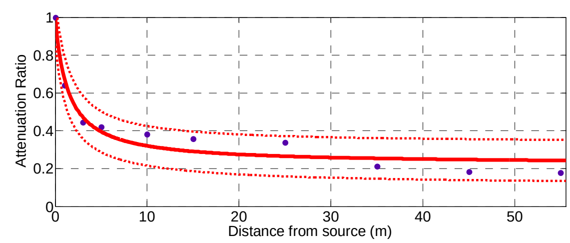

Fig. 14 Attenuation of vibrations for Site B (Vertical axis)

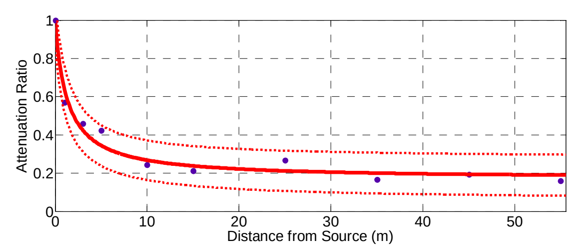

Fig. 15 Attenuation of vibrations for Site B (Horizontal axis)

Our fit to attenuation ratio of vibrations with distance from the source assumes the following functional form:

$$\text{Attenuation ratio} = |a(x)|/|a_{source}| = (p1*x + p2) / (x + q1) \qquad (1)$$

Where x represents the horizontal distance from source in meters. P1, p2 and q1 are determined from curve fitting procedure. $|a(x)|$ denotes the amplitude of acceleration (vertical or horizontal) at x meters distance from the source and $|a_{source}|$ accounts for acceleration amplitude at the source.

Table 5 Variables for the prediction function

Constants	Site A (soil)		Site B (rock)	
	Horizontal	Vertical	Horizontal	Vertical
P1	0.06342	0.06804	0.1701	0.2236
P2	1.225	1.889	1.342	1.429
Q1	1.209	1.874	1.364	1.447

CONCLUSION

Vibration measurement and analyses are vital for dealing with vibration problems in structures located in close vicinity of traffic induced sources. Prediction of traffic induced ground borne vibrations serves as the rationale to select proper measures for mitigation or prevention of vibration problems.

In this study, main objective is the estimation of ground-borne vibration levels at two different sites due to operation of heavy vehicles. Soil type and stratification significantly differs in the sites. First site is composed of layers of clay and sand whereas second site rest mainly on basaltic rock.

For this purpose, site specific vibration surveys are conducted at selected locations in the site. A series of dynamic finite element modeling analyses are performed for predicting actual vibration recordings at different measurement points on the ground. Parameters used in finite element modeling are obtained through geotechnical and geophysical surveys conducted at the site. Calibrated finite element models are further used for predicting the attenuation of vibrations with distance from the source.

Finite element modeling results are in good agreement with the actual acceleration measurements in the considered frequency range. Frequency range of dominant structural responses due to ground borne vibrations induced by heavy vehicles is between 10 Hz to 50 Hz for a single degree of freedom system with 3% damping. It is observed that wave attenuation is slightly better in soil site compared to the rock site.

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